Acoustic Detection, Behavior, and Habitat Use of Deep-Diving Odontocetes

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LONG-TERM GOALS

Passive acoustic monitoring is a key enabling technology in mitigating the effects of Naval activities on sound-sensitive cetaceans. The goals of this project are to obtain and disseminate critical information needed for the design of acoustic monitoring systems.

OBJECTIVES

1. Develop and evaluate passive acoustic detection/classification methods for click and whistle sounds produced by deep-diving toothed whales.

2. Examine the relationships between diving, acoustic behavior, habitat use and group size with implications for acoustic detection and density estimation of toothed whales.

3. Correlate fine-scale oceanographic parameters with foraging behavior of tagged whales to predict habitat suitability and movement patterns.

APPROACH

The performance of an acoustic monitoring system depends not only on the system design and operating protocol, but also on the environment in which it is used and the behavior of the animals to be detected. Thus an integrated approach is needed to obtain the statistics from which to design, and predict the performance, of acoustic detectors. This project continues a pioneering integrated study focused on deep-diving cetacean species of particular concern to the Navy and for which scant information is available regarding acoustic detectability. Tasks within the project comprise:

- Tagging and acoustic recording of beaked whales and pilot whales
- Study habitat choice and use of deep-foraging odontocetes

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14. ABSTRACT

Passive acoustic monitoring is a key enabling technology in mitigating the effects of Naval activities on sound-sensitive cetaceans. The goals of this project are to obtain and disseminate critical information needed for the design of acoustic monitoring systems.

15. SUBJECT TERMS

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- Evaluation and application of acoustic detectors
- Data archive and sharing

Fieldwork is concentrated in two areas with coastal resident populations of deep-diving toothed whales (Blainville's beaked whale, *Mesoplodon densirostris*, and Cuvier's beaked whale, *Ziphius cavirostris*, off the island of El Hierro, and short-finned pilot whales, *Globicephela macrorynchus*, off the island of Tenerife in the Canary Islands [Aguilar, 2006]). These sites are unique in supporting simultaneous visual and acoustic observations of oceanic species with low-cost shore-based operations. In each site, we use three techniques: wide bandwidth acoustic recording buoys, visual survey, and suction cup attached acoustic recording tags (DTAGs). We are also performing habitat assays in zones previously established as consistent foraging sites for beaked and pilot whales.

Data collected during this project and a preceding NOPP represent a unique resource for developing and evaluating acoustic detectors. We are exploring this data at three spatio-temporal levels. At the level of individual vocalizations, buoy and tag recordings are aiding the development of statistical models to predict, and improve, the performance of acoustic detectors. On a dive-by-dive level, we are analyzing DTAG sound and movement data to learn how vocal output relates to habitat, group composition, and behavioral state. Also at this level, comparison of visual sightings against buoy recordings provides a measure of the probability of detecting an animal during a dive cycle. At the largest scale, we are examining visual sightings, and using photo-identification and habitat indicators to describe habitat choice and residence patterns. This will improve our understanding of what constitutes a habitat for deep-diving cetaceans and so aid in predicting their occurrence in other sites.

The project includes a task to make acoustic and movement data collected with tags over the last 8 years available to other researchers via public archives. Publishing this data will facilitate the development of reliable acoustic monitoring systems and enable consistent performance comparisons.

Co-investigators on the project come from the Woods Hole Oceanographic Institution (Johnson and Tyack), the University of La Laguna in Spain (Aguilar and Brito) and the University of Aarhus in Denmark (Madsen). This tightly integrated team has expertise in physiological acoustics (Madsen), behavioral use of sound (Tyack and Aguilar), marine biology (Brito) and acoustics and underwater instrumentation (Johnson). The team is supported by experts in bioacoustics, visual survey, biological and physical oceanography, acoustic detection, and database design.

WORK COMPLETED

Fieldwork

Field work performed in FY2009 comprised:

- A 4-week tagging campaign in El Hierro (Oct. 2008). Key result was an 18 hour DTAG attachment to a Blainville's beaked whale with contemporary acoustic recordings from a drifting buoy.
- Three 7-day seasonal surveys in El Hierro. Methods included passive acoustic monitoring, photo-identification and double visual platforms.
- A 10 day habitat cruise (May 2009) sampling the biological and chemical oceanography off-shore of El Hierro and Tenerife.

Due to the success of the 2008 field campaigns (5 and 24 tags deployed on beaked whales and pilot whales, respectively), tag-based field efforts were minimized in FY2009 to concentrate effort on data analysis. Nonetheless, the fall-2008 field effort in El Hierro yielded an important breakthrough: a DTAG was attached to a beaked whale diving near a drifting vertical array of acoustic recorders. The combination of on-animal and far-field array data allows precise measurement of the distance between the whale and the receiver, yielding a set of echolocation click received at known distances from which to establish acoustic detection rates.

Regular visual surveys, performed in El Hierro since 2003, have provided an important longitudinal view of beaked whale residence patterns (Aparicio et al. 2005; Arranz et al. 2008). Starting in 2008, we added passive acoustic monitoring from drifting hydrophone arrays and double platform visual observations to the surveys as a means to cross-validate visual and acoustic detection of beaked whales. In FY2009, we modified the arrays to include a pair of autonomous hydrophones located at depths of 20 and 300 m on the same cable. These depths are representative of those attainable by towed hydrophone arrays and sonobuoys, respectively, and also bracket the relatively deep thermocline in the tropical waters of the study area. Comparison of the click detections at each depth will provide an indication of the impact of receiver depth on detection probability.

The May 2009 habitat study was performed to characterize the biodiversity and oceanography of the two study areas in the Canary Islands which hold resident but segregated populations of pilot and beaked whales (Aguilar, 2006). Comparison of these biotopes may reveal parameters that govern habitat selection by these similar-sized teutophagus species. The study was performed on a 32m deep-sea research vessel subsidized by the Canary Islands Government. Experts in hydroacoustics, scientific fishing and the taxonomy and ecology of marine organisms, joined the cruise. Participating institutions included La Laguna University (ULL), the Scientific Research Institute of Spain (CSIC) and the Canarian Institute for Marine Research (ICCM). Methods included mesopelagic trawls, hydroacoustic survey, deep water sampling, vertical zooplankton hauls and CTD profiles. Primary production was measured by incubating ^{14}C marked water samples at depth. Sampling locations were based on the foraging sites of pilot and beaked whales tagged in previous campaigns in the same areas.

Data analysis

Analysis of acoustic data from DTAGs and autonomous hydrophones is time-consuming but we have made substantial progress this year. All tag data from beaked whales and most of the tag data from pilot whales collected in 2008 has been examined to the level of individual vocalizations. In addition to overall spectrographic evaluation and listening, a number of parameters are extracted for each vocalization. These include the timing and waveform variability of echolocation clicks along with the distance and strength of echoic objects ensonified by tagged whales. For whistle sounds, the fundamental frequency contour is extracted and the context of the sound is recorded. These analyses result in databases which enable meta-exploration of what is otherwise extremely complex data.

Autonomous acoustic recording buoys, each carrying 2-4 hydrophones have now been deployed on 30 days in El Hierro and Tenerife with contemporaneous visual sightings. The data from 25 of these deployments has been evaluated by visual inspection of spectrograms to determine the location of possible clicks and other vocalizations. Each click is compared in terms of spectrum and waveform with a dataset of known beaked whale clicks derived from on-animal recordings (Zimmer et al., 2005; Johnson et al., 2006). The recordings from deep-shallow hydrophone pairs have been analyzed in the same way and the MARK algorithm will be used to establish relative detection rates. Cross-validation of acoustic and visual detection is achieved by comparing the occurence of clicks with visual sightings. Sightings from the double visual platforms provide an independent means to assess the probability of visual detection of beaked whales from an elevated land station as a function of sighting conditions.

A preliminary taxonomic identification of organisms collected during the habitat cruise is complete although further analyses are being carried out at CSIC and ULL. Most of the species trawled have been found in the stomachs of stranded beaked and pilot whales in the Canary Islands (Santos *et al.* 2007). Samples from skin and muscle of potential prey species of these whales have been taken for isotopic analyses. The isotope ratios of carbon and nitrogen in these tissues are being analyzed by a PhD student at ULL in collaboration with the SIRFER Laboratory at the University of Utah. These will be compared with tissue samples collected from whales stranded in the same area. Water and zooplankton samples are being analyzed at ULL following standard techniques and will be integrated with echosounder-derived biomass estimates and estimates from trawl abundance. These data will be further integrated with tag data to study beaked whale foraging tactics with respect to horizontal and vertical location of potential prey communities (Arranz et al. in prep.).

Data sharing

A growing set of DTAG data and metadata is available on the Woods Hole Open Access Server maintained by the MBL-WHOI library. We have also provided data to mobysound.org, dosits.org and a new photo-identification database. We have prepared extensive databases of click waveforms and inter-click-intervals (ICIs) of Blainville's and Cuvier's beaked whales, pilot whales and sperm whales. These data, derived from tag recordings, are reliable guides to individual vocalization rates and variability, and are valuable for modeling detection probability and for testing passive acoustic detectors. Successful data sharing requires not only availability of data but also the confidence and tools to use it. In addition to conference presentations and outreach efforts, we have published a review paper (Johnson et al., 2009) describing the opportunities and limitations of acoustic tag data, and have participated in analysis projects that exemplify these (Schmidt et al., subm.; Simon et al. in press).

Plans for FY2010

In the final year of the NOPP project, we plan to perform two tagging field studies in El Hierro (Oct. 2009 and April-May 2010) and one study in Tenerife (May-June 2010) targeting beaked whales and pilot whales, respectively. The 2010 studies will use the newly designed DTAG-3 multi-sensor acoustic recording tag along with multiple drifting vertical arrays equipped with new DMON acoustic recorders. We will also field a DMON-equipped profiling float or glider in El Hierro as part of a parallel ONR-funded effort in persistent acoustic detection.

RESULTS

Acoustic detector performance

We have shown previously that beaked whales produce distinctive FM echolocation clicks while foraging enabling the acoustic detection of these cryptic species (Johnson *et al*. 2004, 2006). The recording of a tagged beaked whale with a hydrophone array achieved this year opens the possibility for realistic field assessment of acoustic detector performance. To explore these data, we first developed a precise method for estimating the distance between the tagged whale and the recording array for each detected click (Fig. 1). Calculated distances of between 400 and 3700 m during the recording indicate that passive acoustic detection at ranges of multiple kilometers is possible as predicted by Zimmer et al. (2008). Similar results have also been obtained at the AUTEC range in the Bahamas (Ward et al., 2008) but the portable low-cost system used here makes it possible to repeat these measurements in other environments and with species not present at AUTEC. The data also provide an opportunity to quantify detection probabilities with real data. A set of 1300 clicks from the tagged whale at known distances but variable recording aspects were identified for use in a Monte Carlo simulation. The effects of different distances and ambient noise levels were simulated with an example result in Fig. 1. The relative performance of several detector designs was compared at a fixed false alarm rate of 1 per 20 minutes. We found that, while matched filter detectors can out-perform energy detectors, their performance depends critically on the particular matched filter used suggesting that adaptive or library-based detectors may provide the best performance with beaked whales. We have since discovered that two other whales tagged in 2008 are audible in buoy recordings and these data sets have now been analyzed. The larger multi-individual data set will improve our estimates of detection rate and allow us to assess the degree to which individual variation in click waveform confounds matched filter detectors.

Acoustic behavior

We reported in Johnson et al. (2004) that echoes from prey ensonified by echolocation clicks can be detected in on-animal DTAG recordings. We have since developed a high resolution method for visualizing prey echoes during buzzes, rapid sequences of clicks thought to indicate prey capture attempts (Johnson et al., 2008). The fine detailed view of echoes during buzzes opens the possibility to explore predator-prey interactions and the mechanics of prey capture. We have now applied this technique to the El Hierro Blainville's beaked whale data with an example shown in Fig. 2. Many buzzes contain sudden changes in approach speed due to changes in predator and/or prey movement. Comparing these with accelerometer data measured on the whale reveals strong stereotypy in the tactics of tagged beaked whales: a tightly-coordinated combination of ram (forward thrusting) and sucking is used to capture prey similar to that described for some fish (Holzman et al. 2007). Further analysis of prey behavior in buzzes may help to understand the niche of beaked whales with respect to the organisms found in the mesopelagic trawls.

Last year we reported rasp sounds (rapid sequences of FM clicks) recorded from Blainville's beaked whales with a likely social function. We have since discovered that this species also produces occasional mid-frequency (9-13 kHz) whistles. These novel sounds were recorded from both a tagged whale and other nearby whales during deep dives. Produced at depths of up to 900 m, these are the deepest whistles reported from odontocetes. The whistles are rare and have a relatively low source level but are audible at ranges of 300 m or more and so may serve a social function as with rasps.

A substantial portion of the tag recordings from pilot whales have now been analyzed. These whales show high temporal variability in vocalization rates and we are beginning to identify parameters, such as behavioural state as parameterized by tag sensors and whale gender, that may influence this variability. In addition to echolocation clicks and buzzes, pilot whale produce a variety of pulsed and tonal signals with an apparent communicative function. Some tonal signals are highly stereotyped and their potential function for group recognition, as described for other delphinids, is being investigated. A surprisingly high proportion of social sounds are produced during deep foraging dives perhaps indicating an increased need for contact calls when whales separate to forage. Working with colleagues at Aarhus University, we have estimated the active space of pilot whale vocalizations and evaluated the potential impact of vessel noise on communication range in deep water habitats (Jensen et al. 2009).

We have also advanced our understanding of how sounds from tagged whales are distorted in on-animal recordings, a significant issue with acoustic recording tags (Johnson et al. 2009). On-animal recordings of echolocation clicks contain a slow-decaying low-frequency reverberation or resonance that is not evident in far-field recordings. In examining this component, which is particularly evident in tag data from pilot whales (Fig. 3) and sperm whales, we realised that it is produced by the air-spaces needed to store and recycle air in the odontocete pneumatic sound generator. We have used a click-by-click analysis of the decay rate and resonance frequency of clicks to determine when air recycling occurs during echolocating and how much air is required to produce a click. This result exemplifies the remote-sensing capabilities of tags attached to free-swimming whales. Collectively, the results obtained this year improve our understanding of the acoustic ecology of echolocation and social living in toothed whales which will translate into more detailed models of vocalization rates and detectability, and perhaps a better understanding of their apparent sensitivity to anthropogenic sounds.

IMPACT/APPLICATIONS

National Security

Concern about potential impacts on acoustically-sensitive cetaceans has constrained some Navy training exercises and has led to lengthy court proceedings. The development of reliable methods to predict and verify the presence of cetaceans will provide the Navy with new tools to help balance preparedness with environmental stewardship.

Economic Development

Economic development brings increasing noise to the ocean from ship traffic and oil exploration. An improved understanding of the abundance and habitat of marine mammals and their use of sound will help to make economic growth sustainable.

Quality of Life

The project will contribute to our understanding of deep diving cetaceans, their habitat, and their sensitivity to human interactions. The techniques developed here will also improve abundance surveys and help locate critical populations. These results will facilitate improved regional management with implications on ecosystem health.

Science Education and Communication

The project is focused on disseminating information and developing capacity in the area of acoustic monitoring of cetaceans. Graduate students are involved in all facets of the work. Results from the project have been described at several international conferences, in peer-reviewed scientific literature, and in numerous magazine and internet articles targeted at the general public (both English and Spanish language).

TRANSITIONS

National Security

Observations of undisturbed animals, obtained in this project, have been useful in designing, and interpreting results from, behavioral response studies such as the Navy supported Bahamas BRS. These studies have been designed to inform the acoustic mitigation policy of the Navy.

Quality of Life

Findings from this project have led the government of the island of El Hierro to propose declaring the coastal waters of the island a marine protected area for beaked whales, the first such dedicated to these species.

Science Education and Communication

Twelve journal papers have been submitted or published and three masters level dissertations have been submitted. Acoustic recordings and tag data have been made publicly available as a permanent resource on the Internet. The data includes tag recordings from beaked whales, pilot whales, sperm whales, and right whales.

RELATED PROJECTS

Under funds from the ONR-AMT program and an SBIR to Rite Solutions Inc., we have developed and characterized a self-contained acoustic detector and recorder, the D-MON. This device has been integrated in profiling floats and gliders to create a persistent detection capability. D-MONs are also being used in the drifting buoys in the NOPP project. Detection algorithms developed in the NOPP and AMT projects will be implemented for real-time operation in the D-MON. Data sets acquired under the NOPP will be used to characterize the detection capability of the D-MON.

Funding from SERDP (CS-1188) is supporting the development of a new generation DTAG with enhanced capabilities and longer recording life which will be used in the NOPP study beginning April 2010. New sensors in the tag include GPS, electro-cardiography, and a full inertial navigation sensor.

Research grants from the Spanish and Canary Islands Governments to ULL in FY2010 will extend the habitat studies initiated under the NOPP. A deep-water acoustic and visual survey will be performed over a majority of the Canary Island archipelago providing a spatial context in which to situate the NOPP study areas. Also, a second oceanographic cruise will extend the biological and chemical habitat characterization to an adjacent island, La Palma. A third funded project involves comparison of photo-identification data from El Hierro with photos gathered in neighboring islands to investigate intra-archipelagic migrations of beaked whales.

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REFERENCES

Aguilar de Soto, N. (2006) *Acoustic and diving behaviour of the short finned pilot whale (Globicephala macrorhynchus) and Blainville´s beaked whale (Mesoplodon densirostris) in the Canary Islands. Implications on the effects of man-made noise and boat collisions*. Ph.D. dissertation, University of La Laguna, Canary Islands, Spain.

Aparicio C., Guerra M., Hernández A., Padrón A., Díaz F., Domínguez I., Brito A., Johnson M., Aguilar de Soto N., "Resident and reproductive populations of beaked whales in El Hierro, Canary Islands", European Research on Cetaceans 19th, France, April 2005.

Arranz, P., Aguilar Soto, N. Johnson, M., "Coastal habitat use by Cuvier´s and Blainville´s beaked whales off El Hierro, Canary Islands", European Research on Cetaceans 22nd, Holland, April, 2008.

Holzman R., Day S.W., Wainwright P.C. (2007). "Timing is everything: coordination of strike kinematics affects the force exerted by suction feeding fish on attached prey", J. Exp. Biol. 210:3328-3336.

Johnson M., Madsen P.T., Zimmer W. M. X., Aguilar de Soto N., Tyack P.L. (2004). "Beaked whales echolocate on prey", Proc. R. Soc. Lond. B 271, pp. S383-386.

Johnson M., Madsen P.T., Aguilar Soto N., Tyack P. (2006). "Foraging Blainville's beaked whales (*Mesoplodon densirostris*) produce distinct click types matched to different phases of echolocation", J. Exp. Biol., 209, pp. 5038-5050.

Santos M.B., Martin V., Arbelo M., Fernández A., Pierce G.J. (2007), "Insights into the diet of beaked whales from the atypical mass stranding in the Canary Islands in September 2002". J. Mar Biol Ass. U.K. 87:243-251.

Zimmer W. M. X., Johnson M., Madsen P.T.M., Tyack P.L., "Echolocation clicks of free-ranging Cuvier's beaked whales (Ziphius cavirostris)", J. Ac. Soc. Am., 117, pp. 3919-3927, June 2005.

PUBLICATIONS

Journal papers

Schmidt V., Weber T.C., Wiley D., Johnson M., "Underwater tracking of humpback whales (Megaptera novaeangliae) with HF pingers and acoustic recording tags", Submitted to IEEE J. Oceanic Eng.

Simon M., Johnson M., Tyack P.L., Madsen P.T. (2009), "Behaviour and kinematics of continuous ram filtration in bowhead whales (Balaena mysticetus)", Proc. Royal Soc., doi: 10.1098 / rspb.2009.1135 [published, refereed].

Johnson, M., Aguilar de Soto, N., Madsen, P.T., "Studying the behaviour and sensory ecology of marine mammals using acoustic recording tags". Marine Ecology Progress Series. [in press, refereed]

Jensen, F.H., Bejder, L., Wahlberg, M., Johnson, M., Aguilar Soto, N. and Masden, P.T., "Noise levels and masking potential of whale watching and research vessels around two delphinid species". Marine Ecology Progress Series. [in press, refereed]

Johnson M., Aguilar de Soto N., Performance evaluation of passive acoustic detectors for beaked whales. Proc. of the workshop on beaked whales and sonar, European Cetacean Society, 2009. [in press]

Zimmer, W.M.X., Harwood, J., Tyack, P.L., Johnson, M., Madsen P.T. (2008). "Passive acoustic detection of deep diving beaked whales", J. Ac. Soc. Am. [published, refereed]

Aguilar Soto N., Johnson M., Madsen P.T., Díaz F., Domínguez I., Tyack P., Brito A. (2008). "Cheetahs of the deep sea: sprinting deep foraging in short finned pilot whales". J. Animal Ecol., 77, pp. 936-947. [published, refereed]

Ward, J., Morrissey, R.P., Moretti, D.J., DiMarzio, N., Jarvis, S., Johnson, M., Tyack, P.L., White, C. (2008). "Passive acoustic detection and localization of *Mesoplodon densirostris* (Blainville's beaked whale) vocalizations using distributed bottom-mounted hydrophones in conjunction with a digital tag (DTAG) recording". Can. Acoust. 36:60-73. [published, refereed]

Jones B.A., Stanton T.K., Lavery A.C., Johnson M., Madsen P.T., Tyack P.L. (2008). "Classification of broadband echoes from prey of a foraging Blainville's beaked whale". J. Ac. Soc. Am. 123(3), pp. 1753-1762. [published, refereed]

Johnson M., Hickmott L.S., Aguilar Soto N., Madsen P.T. (2008). "Echolocation behaviour adapted to prey in foraging Blainville's beaked whale (*Mesoplodon densirostris*)". Proc. R. Soc. B (275), 133-139. [published, refereed]

Madsen P.T., Wilson M., Johnson M., Hanlon R., Bocconcelli A., Aguilar Soto N., Tyack P.T. (2007). "Clicking for calamari: can toothed whales echolocate squid (Loligo pealeans)?". Aquatic Biology (1), 140-150. [published, refereed]

Aguilar de Soto, N., Johnson, M., Madsen, P., Díaz, F., Domínguez, I., Aparicio, C., Bocconcelli, A., Militello, C., Brito, A. (2007). "Nuevos descubrimientos sobre cetáceos de buceo profundo en Canarias: relación con su conservación". Makaronesia 9. [published, refereed]

Conference presentations

Beedholm K., Madsen P., Johnson M., "Discriminating beaked whale clicks: there is little reduction in detection performance by the introduction of an effective discrimination step", 5th Animal Sonar Symposium, Kyoto, Sept. 2009.

Johnson M., Aguilar de Soto N., Terray E., Madsen P., "Predator-prey interactions in the deep-sea: a first view of prey behaviour during echolocation buzzes", 5th Animal Sonar Symposium, Kyoto, Sept. 2009.

Madsen P., Johnson M., Aguilar de Soto N., Arranz P., Tyack P., "Beaked whale biosonars in the deep sea", 5th Animal Sonar Symposium, Kyoto, Sept. 2009.

DiMarzio N., Moretti D., Ward J., Morrissey R., Jarvis S., McCarthy E., Johnson M., Tyack P., Claridge D., Dunn C., Marques T., Thomas L., "Passive acoustic density estimation of Blainville's beaked whales (*Mesoplodon densirostris*) using group localization combined with click counting", 4th International Workshop on Detection, Classification and Localization of Marine Mammals using Passive Acoustics, Pavia, Sept. 2009.

Ward J., DiMarzio N., Jarvis S., Moretti D., Morrissey R., Johnson M., Tyack P., "*Mesoplodon densirostris* transmission beam pattern estimated from passive acoustic bottom mounted hydrophones and DTag recordings on multiple whales", 4th International Workshop on Detection, Classification and Localization of Marine Mammals using Passive Acoustics, Pavia, Sept. 2009.

Parks S.E., Clark C.W., Johnson M., Tyack P.L., "Simultaneous acoustic tag and bottom mounted acoustic recorder detection of right whale calls in the Bay of Fundy", Meeting of the Ac. Soc. Am., Portland, May 2009.

Johnson M., Hurst T., Arias A., Aguilar de Soto N., "Validating acoustic monitors for marine animals: field experience with beaked whales and Digital Acoustic Monitors", Meeting of the Ac. Soc. Am., Portland, May 2009.

Aguilar Soto, N., Johnson, M., Tyack, P., Marrero, J., Madsen, P. "Deep communication in beaked and pilot whales". 23rd Conference of the European Cetacean Society. Istambul, Turkey.

Aguilar Soto, N. "Mass strandings as focal events for underwater noise regulation. Challenges of sonar mitigation for beaked whales" Workshop "Beaked whales and active sonar: transiting from research to mitigation" held at the 23rd Conference of the European Cetacean Society. Istambul, Turkey.

Aparicio, C., Aguilar Soto, N., Crespo, A. "Should beaked whales be protected or "data deficient"? a population approach to their status of conservation" 23rd Conference of the European Cetacean Society. Istambul, Turkey.

Boisseau, O., Lacey, C., Lewis, T., Thorne, T., Moscrop, A., Gillespie, D. and Aguilar Soto, N. "Mid-Atlantic surveys for beaked whales: the potential for acoustic prediction of critical habitats" 23rd Conference of the European Cetacean Society. Istambul, Turkey.

Gordon, J., Gillespie, D., Caillat, M., Claridge, D., Moretti, D., Dalgaard Balle, J., Boisseau, O., Aguilar de Soto, N., Viallelle, S., Boyd, I. "Detection and classification of beaked whales using towed hydrophones and real-time software for discrimination and localisation" 23rd Conference of the European Cetacean Society. Istambul, Turkey.

Johnson. M., Madsen, P., Whalberg, M., Dominguez, I., Aguilar Soto, N. "Resonant species and air movement in echolocating deep diving cetaceans" 23rd Conference of the European Cetacean Society. Istambul, Turkey.

Johnson, M. "Quantifying the performance of passive acoustic detectors for beaked whales. Workshop "Beaked whales and active sonar: transiting from research to mitigation" held at the 23rd Conference of the European Cetacean Society. Istambul, Turkey.

Tyack, P. Behavioural responses of beaked whales to sound. Workshop “Beaked whales and active sonar: transiting from research to mitigation” held at the 23rd Conference of the European Cetacean Society. Istambul, Turkey.

Aguilar Soto, N., Johnson, M., Madsen, P., Díaz, F., Domínguez, I., Tyack, P., Brito, A. “La estrategia guepardo del calderón de aleta corta “*Globicephala macrorhynchus*” en las Islas Canarias”. XII Spanish and IX Iberoamerican Ethology Conference. September, Valencia, 2008.

Arias, A., Johnson, M., Aguilar, N., Madsen, P., Mohl, B. “Acoustic detection of beaked whales from autonomous recording buoys” Conference of the American and European Acoustic Societies. París, July, 2008.

Arranz, P., Aguilar Soto, N. Johnson, M., “Coastal habitat use by Cuvier´s and Blainville´s beaked whales off El Hierro, Canary Islands” European Research on Cetaceans 22nd, Holland, April, 2008.

Aguilar Soto, N. “Functions and effects of sound on cetaceans” Western African Talks for the Conservation of Small Cetaceans. Organized by CMS (UNESCO Agreement for the conservation of migratory species. Tenerife. October, 2007.

Books, reports, dissertations and popular articles

Johnson C., "Diving with beaked whales", video mini-documentary available at www.whaletrackers.com.

Johnson M., "Field investigation of the detectability of beaked whales using passive acoustic sensing". Report to Rite-Solutions Inc., July 2009.

DTAG data on the Woods Hole Open Access Server: https://darchive.mblwhoilibrary.org/handle/1912/1725

Evans, P.G.H., Aguilar de Soto, N., Herman, J. S. & Kitchener, A.C. (2008). “Blainville’s beaked whales (*Mesoplodon densirostris*)”. In *Mammals of the British Isles*. 4th edition. The Mammal Society, UK. [in press, refereed]

Aparicio, C. Estudio de población de los zifios de Blainville y de Cuvier (*Mesoplodon densirostris* y *Ziphius cavirostris)* en El Hierro. Dissertation for Master's in Biology, Univ. La Laguna, Tenerife, Sept. 2008.

Arias, A. Análisis de chasquidos en cetáceos de buceo profundo y aplicación en detección acústica pasiva. Dissertation for Master's in Biology, Univ. Complutense, Madrid, Sept. 2008.

Arranz, P. Cetáceos avistados en el entorno de la isla de El Hierro, en el marco del INTERREG “BIONATURA”. Report for the Council of Environment of the Canary Islands Government, August 2008.

Madin K., "Pilot whales - the 'cheetahs of the deep sea'", Oceanus 46 (3), pp. 36-38.

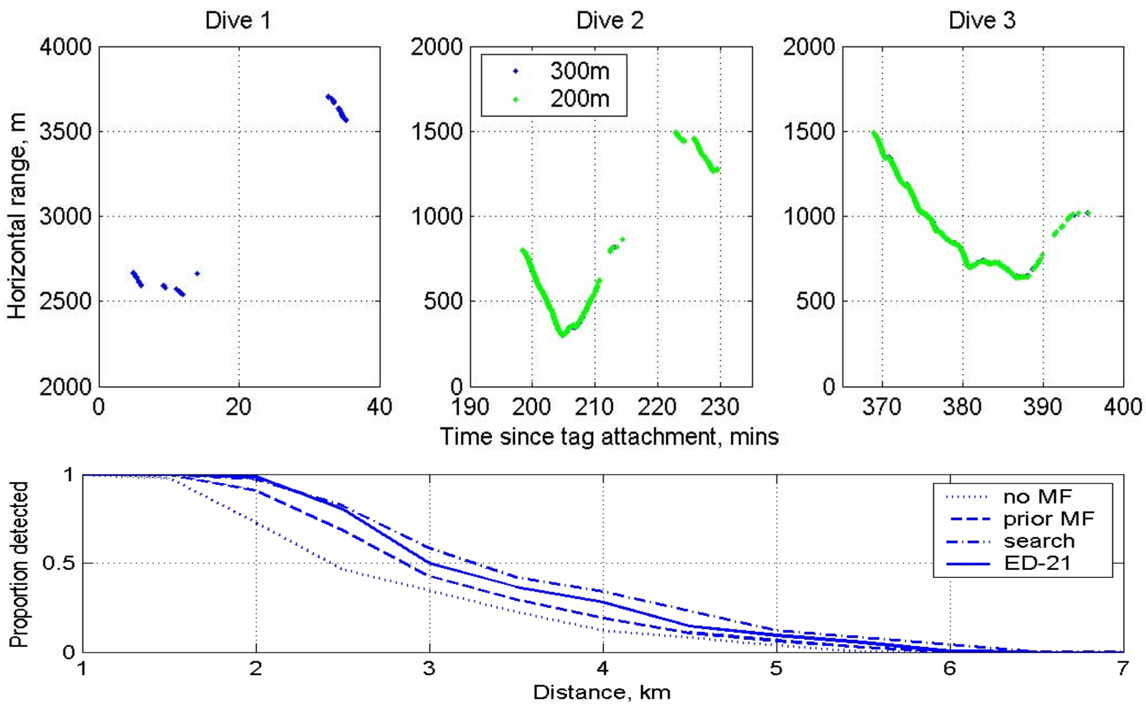

Fig. 1: Passive detection of clicks from a tagged. Blainville's beaked whale Upper panel: distance between a tagged beaked whale and a drifting acoustic recording buoy during three foraging dives. In two dives, independent range estimates were obtained from hydrophones at 200 and 300 m depths and the depth estimates coincide closely (<3 m RMS error). Lower panel: Monte Carlo simulation of individual click detectability as a function of distance and detector algorithm using real click waveforms. A set of 1300 beaked whale clicks were used in the simulation including on and off-axis recordings. The ambient noise level was equivalent to a Wenz sea-state 3 and the effective false alarm rate was fixed at 1 per 20 minutes. Algorithms tested included a simple threshold detector ('no MF'), two different matched filter detectors ('prior MF' and 'search') and an energy detector ('ED21'). We are currently studying how to deduce the probability of detecting individual whales as a function of listening duration from simulations like this.

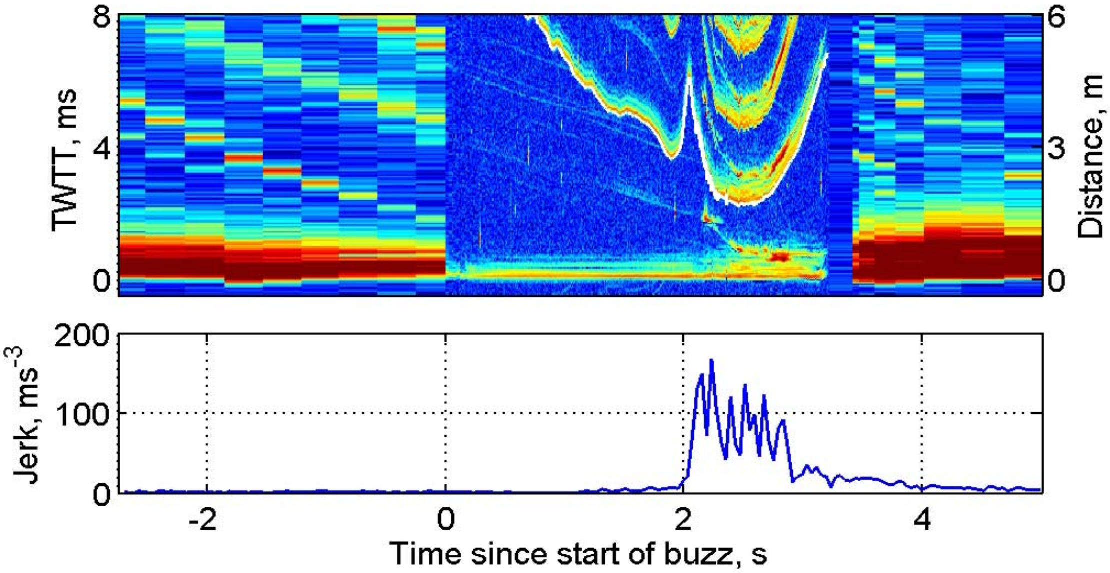

Fig 2: High-resolution echogram of a prey capture. Analysis of the echo returns from prey during prey capture attempts (buzzes) made by tagged beaked whales provides a wealth of information about both the foraging tactics of this predator and the behavior of its prey. Echograms are formed by displaying the envelope of the echo returns for each out-going click (each vertical colored bar represents one click with warm colors representing a strong echo return; the white line indicates the subsequent out-going click and marks the limit of unambiguous ranging [Johnson et al. 2008]). In this example, the prey item is approached steadily until near the end of the buzz at which point the closing speed suddenly increases (see the faint sloping line in the upper figure which changes slope at about 2.1 s into the buzz) in tandem with a sudden change in acceleration of the whale (lower jerk plot). Reconstruction of the movements of the whale from the tag sensors indicate that the final phase of most buzzes involves a carefully coordinated combination of ram (forward thrusting) and buccal suction to acquire prey. TWTT = two-way travel time to the prey in milliseconds, translated into distance in meters on the right hand side of the graph.

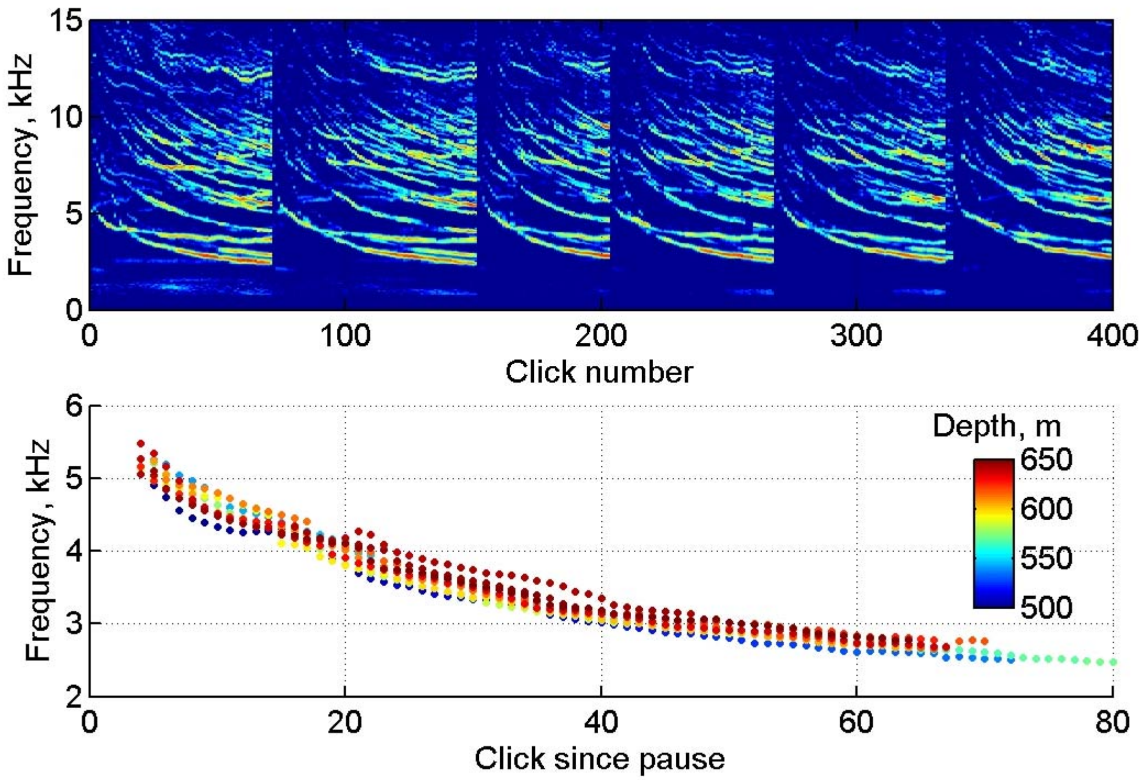

Fig. 3: Resonances in echolocation clicks recorded by a DTAG on a short-finned pilot whale. When recorded close to the vocalizing animal, clicks have distinctive resonances that reveal the movement of air in the pnuematic sound generator in the whale's head. Upper panel: resonance frequencies of a series of 400 clicks made by a tagged pilot whale diving between 500 and 700 m depth. The periodic changes every 50-80 clicks coincide with short pauses in echolocation and indicate when the whale recycles air. The pattern of decreasing resonance frequency between recycling moments suggests that the resonances come from the vestibular sacs above the phonic lips, i.e., the sacs that receive air after each click is produced. Lower: The lowest resonance frequency is closely correlated with click count since a pause. An estimate of the vestibular sac volume and the amount of air required to produce a click can be derived from the slope of these curves.